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Mineralogical and Petrological Constrains on Permian Contact Metamorphism at the Rims of the Ifinger Granodiorite and the Kreuzberg Granite (South-Tyrol, Italy)

Stefan WYHLIDAL[1)], Werner Friedrich THÖNY[1)], Peter TROPPER[1)*)] & Volker MAIR[2)]

[1)] Institute of Mineralogy and Petrography, Faculty of Geo- and Atmospheric Sciences, University of Innsbruck, Innrain 52, A-6020 Innsbruck, Austria;

[2)] Amt für Geologie und Baustoffprüfung, Eggentalerstrasse 48, I-39053 Kardaun (BZ), Italy;

[*)] Corresponding author, peter.tropper@uibk.ac.at

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Abstract

The Ifinger/Ivigna granodiorite and the Kreuzberg/Monte Croce granite were emplaced into the Southalpine basement (Brixen Quartzphyllite) during the Permian (290-270 Ma). Due to the close vicinity of major fault lines such as the Judicarian Line and the Völlan Line, the contact aureoles of both intrusions are strongly deformed and underwent substantial retrogression. Therefore almost no field relations can be observed anymore. The only visible contact aureole adjacent to the Ifinger granodiorite is located at the SW rim of the intrusion in the city of Meran (Gilf ravine). Samples from this contact show typical hornfels textures and the Variscan foliation is nearly obliterated. Unfortunately most samples are strongly altered and only in one location the contact metamorphic assemblage: andalusite + biotite + muscovite + plagioclase + pinite (muscovite/chlorite aggregates) + quartz was observed. Ti-in-biotite thermometry yielded a temperature of 667±15°C which is too high to reconcile the observed mineral assemblage with the petrogenetic grid of Pattison et al. (2002). Contact metamorphic samples from the Kreuzberg granite were only encountered as cuttings in the course of a deep drilling project near Meran. Every five meters, a sample was taken from the cuttings but the samples represent mixtures of minerals and rock fragments from different depths, and therefore the mineral zonation of the contact aureole is somewhat obscured. In a depth of ca. 1600 meters contact metamorphic rock fragments of the Brixen Quartzphyllite showing the assemblage andalusite + biotite + plagioclase + K-feldspar + pinite + quartz were encountered. Unfortunately, due to strong retrogression, no fresh cordierite has been found in the cuttings. Two-feldspar thermometry yielded temperatures in the range of 570°C to 640°C. Ti-in-biotite thermometry yielded also a slightly too high maximum temperature of 677±19°C. In both localities, the occurrence of these andalusite-bearing assemblages limit pressures to <0.3 GPa and temperatures of <640°C according to the petrogenetic grid of Pattison et al. (2002) and the aluminium silicate triple point of Pattison (1992). Comparison with the contact metamorphic mineral assemblages from the similar contact aureole from the Brixen Granodiorite (Wyhlidal, 2007a, b; Wyhlidal, 2008), shows that the P-T conditions of the observed mineral assemblages from both contact aureoles represent the innermost parts of the aureoles.

Der Ifinger Granodiorit und der Kreuzberg Granit intrudierten im Perm (290-270 Ma) in das südalpine Basement (Brixner Quarzphyllit). Durch die unmittelbare Nähe von großen Störungssystemen wie der Völlaner- und der Judikarien Linie sind bei beiden Intrusionskörpern die Kontaktzonen fast zur Gänze tektonisch und mineralogisch retrograd überprägt worden. Die einzige noch erhalten gebliebene Kontaktaureole des Ifinger Granodiorits konnte am SW Rand der Intrusion in der Stadt Meran in der Gilfklamm beobachtet werden. Diese Hornfelse sind durch die Mineralparagenese Andalusit + Biotite + Muskovit + Plagioklas + Pinit (Muskovit und Chlorit nach Cordierit) + Quarz charakterisiert. Temperaturen konnten auf Grund der starken retrograden Überprägung ausschließlich mit dem Ti-in-Biotit Thermometer berechnet werden und ergaben eine Temperatur von 667±15°C direkt am Kontakt der Intrusion, die allerdings zu hoch ist um mit dem petrogenetischen Grid von Pattison et al. (2002) kompatibel zu sein. Kontaktmetamorphe Proben aus der Aureole des Kreuzberg Granits wurden nur in den Cuttings der Tiefbohrung bei Sinich angetroffen. Alle fünf Meter Bohrfortschritt wurde zwar eine Probe gezogen und auf deren Mineralbestand analysiert, aber bei dieser Technik handelt es sich immer um Mischungen von Gesteinen aus unterschiedlichen Tiefen. In einer Tiefe von 1600 m konnten kontaktmetamorphe Gesteinsfragmente mit der Paragenese Andalusit + Biotit + Plagioklas + Alkalifeldspat + Pinit + Quarz beobachtet werden. Temperaturen konnten mit dem Zwei-Feldspatthermometer und dem Ti-in-Biotit Thermometer ermittelt werden und ergaben 570°C bis 640°C bzw. 677±19°C als maximale Temperaturen, wobei die Ti-in-Biotit Temperaturen ebenfalls wieder zu hoch sind. Die Anwendung des revidierten Aluminiumsilikat Tripelpunkt von Pattison (1992) und der petrogenetischen Netze von Pattison et al. (2002) limitieren in den andalusitführenden Paragenesen in beiden Hornfelsen die P-T Bedingungen auf <0.3 GPa und <640°C Da es sich hier auch um ehemalige südalpine Quarzphyllite handelt, können die P-T Bedingungen dieser Kontaktfelse mit der Kontaktaureole des Brixner Granodiorits (Wyhlidal, 2007a, b; Wyhlidal, 2008) verglichen werden, und repräsentieren demnach die innersten Bereiche der Kontaktaureole.

1. Introduction

Granitic plutons formed by partial melting of continental lower crust are important markers of geodynamic processes because such magmas crystallize in a shallow continental crust thus causing thermal metamorphism of the country rocks. In the Eastern- and Southern Alps, large Permian (290-270 Ma) granite massifs (Brixen granite complex, Ifinger granodiorite, Kreuzberg granite) occur along the tectonic border namely the Periadriatic Lineament (PAL), which separates the Southalpine domain from the Austroalpine units. In the Southalpine, Permian magmatism occurs as both, intrusive and extrusive rocks (e.g. Bonin et al., 1993; Visonà, 1982).

In contrast to the Permian magmatic evolution, information on the extent of the accompanying Permian contact metamorphic overprint is extremely scarce in both units. In the Austroalpine very few data on this contact metamorphic event exist, which is due to the subsequent strongly pervasive Alpine overprint that obscured many pre-Alpine features. The only data from the Austroalpine domain come from the areas south of the SAM (Southern Limit of Alpine Metamorphism) near the Periadriatic Lineament, where Alpine metamorphism and deformation was weak (Hoinkes et al., 1999). In this area, a detailed investigation was performed on the contact aureole adjacent to the 280-240 Ma old Eisenkappel granite which is part of the Karawanken granite (Exner, 1972, 1976). Monsberger et al. (1994) documented an increasing contact metamorphic overprint from the outer muscovite + quartz zones (520°C) to the inner andalusite + K-feldspar zones (690°C). Further south, the only data available are about the contact metamorphic overprint associated with the intrusion of the Martell granite into the micaschists and paragneises of the Peio Unit of the Austroalpine Ortler Campo Crystalline. This lead to the formation of staurolite + sillimanite + garnet (Mair et al., 2006).

In the Southalpine domain, the Permian intrusive complexes of the Brixen-, Ifinger- and Kreuzberg granitic/granodioritic plutons are aligned along the Periadriatic Lineament, and cover an area of ca. 200 km^2 (Figure 1). Contact aureoles have been identified at the rims of all three plutons but almost no P-T-t data are available from the Ifinger- and Kreuzberg contact aureoles. On the other hand, contact metamorphism at the southern rim of the Brixen granodiorite has been thoroughly investigated and first results were published by Wyhlidal et al. (2007a, b, 2008). Therefore it is the aim of this paper to provide mineral chemical and petrological (P-T) data from the contact aureoles adjacent to the Ifinger- and Kreuzberg plutons.

2. Geological setting

Plutonic rocks prevail in the western- (Massiccio dei Laghi) and eastern Southalpine (Brixen-, Ifinger-, Kreuzberg-, Cima d'Asta plutons), while volcanics prevail in the central Southalpine (Bargossi et al., 1998). Magmatic activity is restricted to the lower Permian with plutonites and volcanics mostly in the range 285-275 Ma (Barth, 1994; Barth et al., 1994; Borsi et al., 1972; Del Moro and Visonà, 1982; Di Battistini et al., 1988; Klötzli et al., 2003; Marocchi et al., 2008; Rottura et al., 1997; Schaltegger and Brack, 1999; Stähle et al., 2001; Visonà, 1982, 1995). The plutons are composite and granite and granodiorite are the most frequent lithotypes with significant portions of tonalite, quartz-diorite and quartz-gabbro. Geological and geochronological data indicate two major intrusive episodes (Bonin et al., 1993; Boriani et al., 1995; Visonà et al., 1987; Visonà, 1995). The first episode (Late Carboniferous/Early Permian) is characterized by abundant intermediate rocks such as quartz-diorite and quartz-gabbro with minor tonalite, granodiorite and granite. The second episode (Permian) is dominated by granites and granodiorites with peraluminous plutonites such as andalusite + cordierite- and garnet-bearing granites. A geodynamic interpretation of these plutons is still uncertain since two tectonomagmatic models exist which point to either magmatism in response to post-orogenic lithospheric extension (e.g. Rottura et al., 1997, 1998) or to an orogenic Andean-type continental margin (e.g. Di Battistini et al., 1988) although geochemical evidence is in favour of the first model (e.g. Marocchi et al., 2008).

The Kreuzberg granite is located near Lana (10 km SW of Meran) and bordered by two tectonic fault lines. The Periadriatic Lineament represents the north-western boundary and the Völlan Line the south-eastern border. In the south-western part a continuous stratigraphic sequence from the intrusion to the higher Permian extrusive rocks including a small band of basement in between is developed. New data (Marocchi et al., 2008) show that these rhyolitic rocks represent the first large effusive activity of the Athesian Volcanic Group (AVG, former "Bozner Quarzporphyrkomplex"). Geochronological data on zircon yielded an age of ~285 Ma for the effusive as well as for the intrusive rocks. Rottura et al. (1997) yielded younger ages of 273±3 Ma for the Kreuzberg granite using

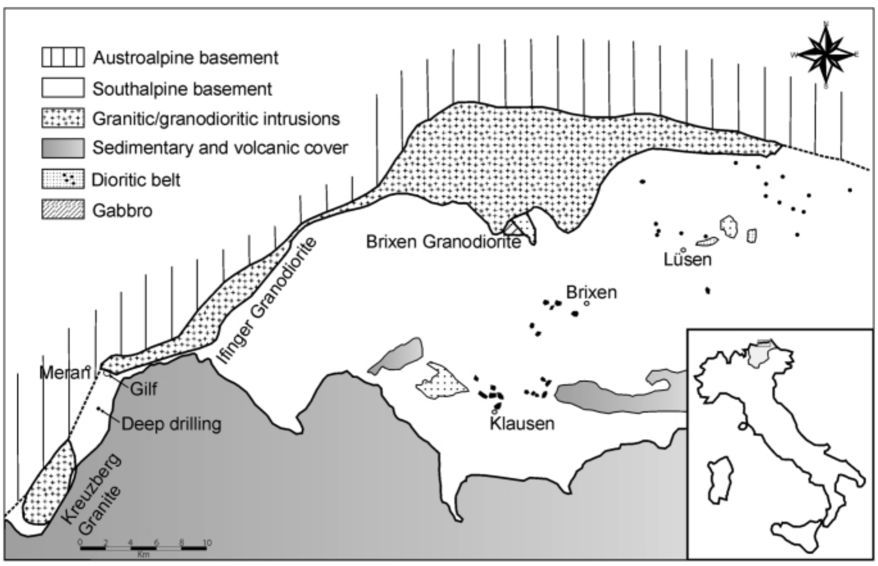

Figure 1: Simplified geological map of the central-eastern Southern Alps illustrating the distribution of the Permian volcanic and plutonic rocks.

biotite Rb/Sr data.

The Ifinger granodiorite occurs in a very similar tectonic situation. The magmatic body is also bordered by two large tectonic systems, the Meran-Mauls fault a part of the Periadriatic Lineament (PAL) and the Naif Lineament (Irschara and Pomella, 2006). The PAL limits the granodiorite to the Austroalpine crystalline basement in the northwest and the Naif Lineament represents a tectonic border where the Permian plutonic rocks were thrusted onto the Southalpine. The Ifinger intrusion represents a calc-alkaline series, similar to the Kreuzberg granite, which mainly consists of granodiorites with minor tonalites and granites. The bulk composition is meta-aluminous to peraluminous (Bonin et al., 1993; Aquafredda et al., 1997; Rottura et al., 1998). Within the granodiorite several mafic enclaves appear which seem to be areas of a higher fluid content within the melt. In addition, these enclaves show hints for mingling processes and chemical assimilation (Rottura et al., 1998). Borsi et al. (1972) presented Rb/Sr whole rock isochron ages of 291±2 Ma for the Ifinger granodiorite and an average age for the Kreuzberg-Ifinger intrusions of 286±2 Ma. Rb/Sr dating on biotites yielded younger ages in the range of 278-271 Ma (Acquafredda et al., 1997; Rottura et al., 1997).

3. Field relations of contact metamorphism

Although the Kreuzberg Granite and the Ifinger Granodiorite have been well studied (e.g. Acquafredda et al., 1997; Bargossi et al., 1981; Del Moro and Visonà, 1982; Visonà et al., 1987; Visonà, 1982, 1995), information on the extent of the accompanying contact metamorphism are extremely scarce. At the Ifinger pluton, remnants of a contact aureole were identified at its southern rim by Künzli (1899) and Sander (1906, 1929). Künzli (1899) and Andreatta (1937) described hornfelses adjacent to the Kreuzberg pluton along its northern rim. These authors also reported the growth of biotite and andalusite in the contact areas. The outcrops of the hornfelses at the northern rim of the Kreuzberg granodiorite do not exist anymore because the landscape in the area of Meran and especially in the area of the northern part of the Kreuzberg intrusion has been gradually transformed into apple plantations during the last century. On the other hand, between October 2001 and January 2002 a deep drilling project in the small village Sinich/Sinigo was done in order to explore for thermal water in the area near Meran between the Periadriatic Lineament in the north and the Völlan Line in the south. The drilling was running perpendicular to the surface to a depth of about 800 m and then the drilling turned westward. The endpoint was located in a depth of 2300 m, 800 m further west from the starting point. Although a sample was taken from the cuttings of this drilling by the Geological Survey of Italy every five meters, most samples represent mixtures of several depth stages due to the nature of cuttings. In a depth between the surface and 675 m fluviatile-lacustrine clastic sediments and conglomerates were observed. Beyond the depth of 675 m the Southalpine basement (Brixen quartzphyllite) was encountered. This basement is characterized by the mineral assemblage muscovite + chlorite + quartz ± feldspar. In a depth between 750 m and 1590 m newly formed biotite has been observed and is thought to represent the first evidence for an incipient contact metamorphism. In a depth between 1590 m and 1760 m typical hornfelses occur. Since the samples represent mixtures of minerals and rock fragments of the granodiorite and the contact metamorphic quartzpyllites, the mineralogical zonation of the contact aureole is somewhat obscured. In a depth between 1780 m and 1920 m only granodioritic rock fragments of the Kreuzberg intrusion were observed. At a depth of 1920 m the Völlan Line was crossed and the samples below the granodioritic intrusion, belonging to the Southalpine basement, did not show any evidence of contact metamorphism anymore.

The contact aureole adjacent to the Ifinger granodiorite is also strongly altered and shows abundant brittle deformation features due to the close vicinity of major fault lines such as the Judicarien Line, the Völlan Line and the Naif Line. Only one outcrop at the SW rim of the Ifinger granodiorite in the city of Meran (Gilf ravine) near the Zeno castle was observed which seems not to be affected by those major fault systems.

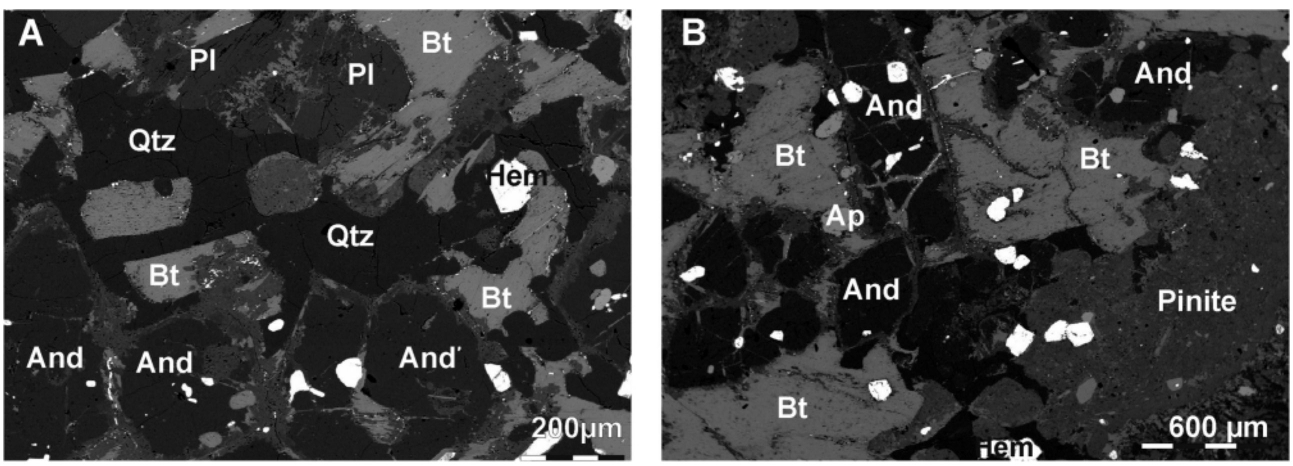

Figure 2: Backscattered electron (BSE) images illustrating the textural relations in the contact aureole of the Ifinger granodiorite and (A) showing the newly formed minerals andalusite (And), biotite (Bt), plagioclase (Pl) and (B) cordierite (Pinite). Qtz: quartz, Ap: apatite, Hem: hematite. Sample CIF.

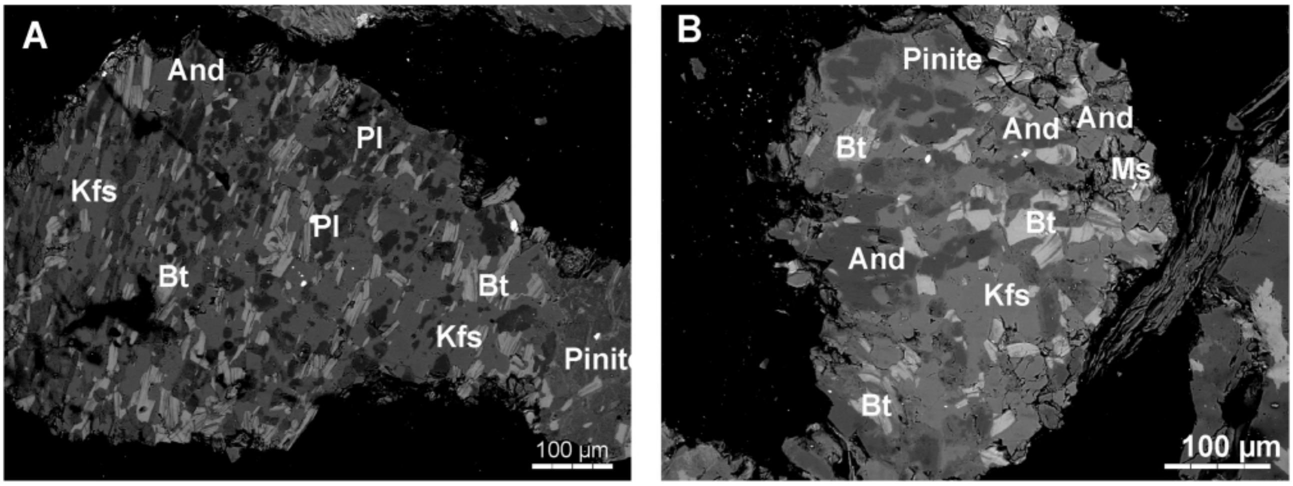

Figure 3: Backscattered electron (BSE) images illustrating the textural relations of contact metamorphosed rock fragments of the Kreuzberg contact aureole. (A) Plagioclase + K-feldspar-bearing fragment, (B) Muscovite-bearing fragment. Newly formed minerals are andalusite (And), biotite (Bt), plagioclase (Pl), K-feldspar (Kfs) and cordierite (Pinite). Sample CKB.

The contact metamorphic pelitic rocks adjacent to the Ifinger granodiorite occur over a distance of ca. 50 m and appear macroscopically as bluish massive hornfelses.

4. Petrography

Thermally unmetamorphosed quartzphyllite: Most of the basement (Brixen quartzpyllite) is comprised of monotonous quartzphyllites, which were pervasively affected by the Variscan metamorphic and tectonic overprint. Due to its now slightly tilted position, the basement shows a metamorphic gradient, which increases from southeast towards northwest (Sassi and Spiess, 1993). In the area of Toblach, the basement shows the lowest peak metamorphic conditions with temperatures of 350-400°C and a pressure of ca. 0.4 GPa. The metamorphic conditions increase towards the northwest and reach maximum P-T conditions in the area of Brixen. In this area calculated P-T conditions yielded temperatures of 450-550°C and pressures of 0.5-0.65 GPa (Ring and Richter, 1994). The thermally unmetamorphosed samples of the northernmost Brixen quartzphyllite contain the mineral assemblage muscovite + chlorite + biotite + plagioclase + albite-rich plagioclase + garnet + quartz ± K-feldspar and accessory minerals such as zircon + monazite + apatite + ilmenite ± rutile ± titanite. Garnet always occurs as porphyroblasts with a diameter of 1 mm up to 2 mm and often contains inclusions of quartz, ilmenite and apatite. The garnets are always continuously zoned. Muscovite and chlorite typically comprise the Variscan foliation.

Hornfels: Cordierites are in both aureoles always completely altered to grey-brown-yellow cryptocrystalline aggregates containing muscovite (sericite) and chlorite which form pinite and hence no microprobe analyses could be obtained. The old Variscan foliation and mineral assemblage is almost completely obliterated by the contact metamorphic recrystallization and development of the mineral assemblage: andalusite + cordierte (pinite) + plagioclase + biotite + muscovite + quartz + ilmenite + rutile + hematite in the samples from the Ifinger contact aureole (Figure 2A, sample CIF). Biotite occurs in the Ifinger contact aureole as large crystals, up to 400 µm in diameter, with abundant inclusions of rutile. As accessory minerals apatite, zircon, and rarely tourmaline can be observed. Contact metamorphic rock fragments from the Kreuzberg granite (sample CKB) are characterized by the mineral assemblage andalusite + biotite + plagioclase + K-feldspar + cordierite (Pinite) + quartz (Figures 3A, B) and seem to represent the highest grade of

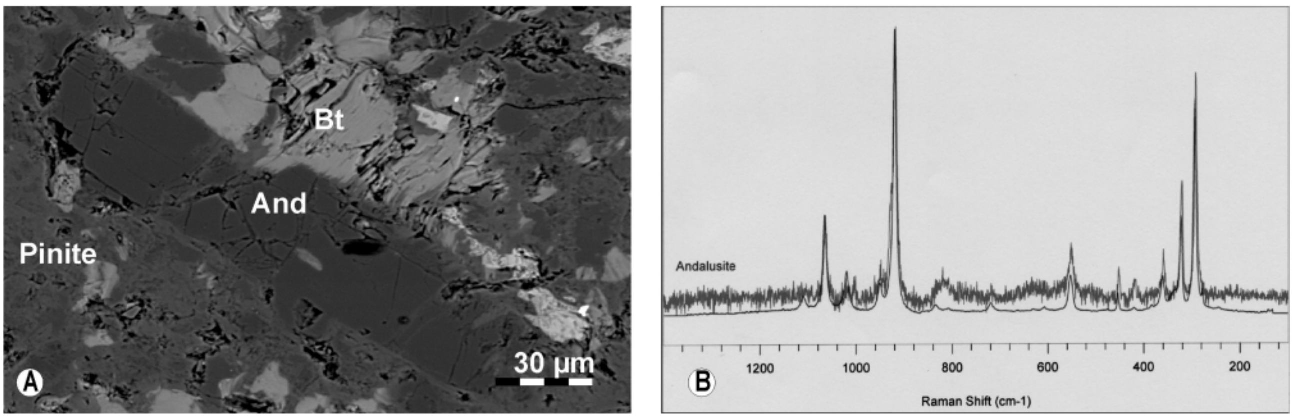

Figure 4: (A) BSE image of an aluminium silicate; (B) micro Raman spectrum of this aluminium silicate which was identified as andalusite. Sample CIF.

contact metamorphism. Plagioclase is often rimmed by albite-rich feldspar. Aluminum silicates were identified as andalusite using micro-Raman spectroscopy (Figures 4A, B).

Intrusions: The mineral assemblage of the Kreuzberg granite (sample KB) is simple, showing K-feldspar + plagioclase + biotite + quartz (Bargossi et al., 1981). The Ifinger granodiorite shows the mineral assemblage plagioclase + quartz + biotite + amphibole + K-feldspar ± rutile ± ilmenite ± apatite ± zircon ± aluminum silicate. Plagioclase occurs in the Ifinger granodiorite (sample IF) as large idiomorphic crystals with a grain size up to 500 µm. Chlorite which mainly appears in the vicinity to fault systems is attributed to a retrograde mineral assemblage together with clinozoisite/epidote. The aluminum silicates occur as large euhedral crystals with a length of up to 1000 µm and were also identified as andalusite using micro-Raman spectroscopy.

5. Analytical techniques:

About 20 thin sections of hornfelses form the contact aureole of the Ifinger granodiorite and about 30 cuttings of the drilling near Sinich were investigated using a polarization microscope. A JEOL 8100 SUPERPROBE electron microprobe was used for analysing the mineral compositions at the Institute of Mineralogy and Petrography at the University of Innsbruck. Analytical conditions were 15 kV acceleration voltage and 10 nA beam current. Natural and synthetic mineral standards were used for calibration. The counting times were 20 sec. for the peak and 10 sec for the background. Most data were obtained with point mode, except for feldspar, which was analyzed using a rastered beam whose size was dependent on the crystal size to prevent the volatilization of alkalis. In addition, a HORIBA JOBIN YVON LabRam-HR 800 micro-Raman spectrometer was used to identify the aluminum silicates.

6. Mineral chemistry

6.1 Hornfelses

The X_{Mg} values of biotites from the Ifinger contact aureole are constant and range from 0.38 to 0.42 (average value = 0.39±0.01) and the Ti [apfu] content ranges from 0.28 to 0.38 (average value = 0.35±0.03 apfu). Newly formed biotite from the Kreuzberg contact aureole can be distinguished from biotite in the granodioritic rock fragments based on its composition as shown in Figure 5. Newly formed biotites are characterized by an Al-rich (Al_{tot} = 3.7±0.12) composition when compared to the granodioritc biotites (Al_{tot} = 2.6±0.004). The Ti [apfu] content of these biotites ranges from 0.32 to 0.45 apfu (average value = 0.39±0.04) and X_{Mg} ranges from 0.29 to 0.37 (average value = 0.32±0.03). Representative EMPA analyses of biotites are summarized in Table 1.

Plagioclase is characterized by an average X_{An} content of 0.28±0.002 in the Ifinger contact aureole. Plagioclase from the Kreuzberg contact aureole also shows a similar anorthite content of 0.30±0.03. Representative EMPA analyses of plagioclase are shown in Table 2.

Alkali feldspar is only observed in the rock fragments of the drilling in the Kreuzberg contact aureole. Based on their X_{Ab} contents two different generations of K-feldspar can be distinguished: The first generation is characterized by a lower average X_{Ab} content of 0.09±0.01 and the second generation by a higher X_{Ab} content of 0.15±0.03. These data suggest that the first generation (low albite content) formed at a lower temperature in an outermost area of the contact aureole and the second generation (high albite content) formed at a higher temperature in an inner area of the contact aureole. Representative EMPA analyses of K-feldspar are given in Table 3.

Sample	Bt CKB 1	Bt CKB 2	Bt CKB 3	Bt KB 1	Bt KB 2	Bt KB 3	Bt CIF 1	Bt CIF 2	Bt CIF 3
SiO_2	33,38	33,75	33,57	35,72	35,51	35,75	35,99	35,87	35,69
TiO_2	3,73	3,49	3,30	3,74	3,56	3,79	3,35	3,20	3,29
Al_2O_3	20,20	20,42	20,51	14,11	14,05	13,99	18,29	18,47	18,78
FeO	21,84	21,45	19,91	23,64	23,39	23,36	21,33	21,83	20,94
MnO	0,26	0,28	0,26	0,52	0,41	0,67	0,25	0,21	0,27
MgO	5,23	5,15	6,23	8,27	8,53	8,41	7,38	7,47	7,38
CaO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Na_2O	0,17	0,09	0,09	0,17	0,13	0,13	0,22	0,22	0,15
K_2O	9,60	9,64	9,87	9,17	9,17	9,24	9,37	9,39	9,71
Total	94,41	94,27	93,74	95,35	94,76	95,34	96,17	96,67	96,22
Si	5,222	5,268	5,242	5,591	5,588	5,594	5,476	5,443	5,430
Ti	0,439	0,410	0,388	0,441	0,422	0,446	0,384	0,366	0,377
Al	3,724	3,757	3,774	2,603	2,606	2,581	3,280	3,303	3,367
Fe^{2+}	2,857	2,800	2,600	3,094	3,078	3,057	2,715	2,770	2,664
Mn	0,034	0,037	0,034	0,070	0,055	0,089	0,032	0,027	0,034
Mg	1,219	1,198	1,450	1,929	2,000	1,962	1,674	1,689	1,673
Ca	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Na	0,050	0,028	0,027	0,051	0,039	0,039	0,064	0,065	0,045
K	1,915	1,919	1,965	1,830	1,840	1,844	1,818	1,817	1,884
xMg	0,299	0,300	0,358	0,384	0,394	0,391	0,381	0,379	0,386

Table 1: Representative electron microprobe analyses of biotite. CKB: biotite analyses from the Kreuzberg contact aureole; CIF: biotite analyses from the Ifinger contact aureole; KB: biotites from the Kreuzberg granite. Formulae were calculated on the basis of 22 oxygens using the computer program NORM Version 4.0 (Ulmer, 1993, written com.). n.d.: not detected.

6.2 Intrusions

Biotites from the Kreuzberg granite are characterized by an X_{Mg} (Mg/Mg+Fe) value of 0.38±0.02 and a low

Al_{tot} content of 2.6±0.004 (Figure 5). The Ti [apfu] content ranges from 0.36 to 0.45 (average value = 0.40±0.02 apfu). Representative analyses of biotite are summarized in Table 1.

Amphibole was observed in samples from the Ifinger granodiorite amphibole (Table 4). The amphiboles show Al_{tot} contents of 1.202 to 1.255 apfu. Since Ca ranges from 1.636 to 1.697 apfu, the amphiboles were classified as calcic amphiboles and most amphiboles are hornblendes/magnesio-hornblendes according to Leake et al. (1997, 2004) as shown in Figures 6A, B.

Plagioclase: Only rims of plagioclase were analyzed which coexist with amphiboles and show a chemical composition of X_{An} = 0.37-0.42, X_{Ab} = 0.57-0.61 and X_{Or} <0.04. Representative EMPA analyses of amphiboles and plagioclase are summarized in Table 4.

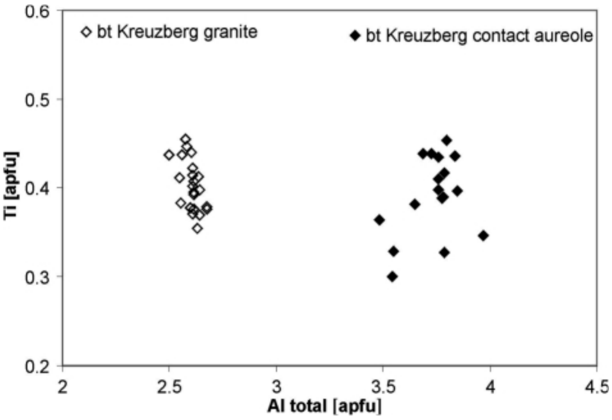

Figure 5: Ti [apfu] vs. Altot plot showing the chemical difference between biotite compositions from the cuttings and the Kreuzberg granite. Samples CKB and KB.

7. Thermobarometry

7.1 Intrusion thermobarometry

The Al-in-hornblende barometer calibrated by Schmidt (1992) was used for samples from the Ifinger granodiorite, although in most cases this barometer yields only limiting information due to the complex nature of the coexisting mineral assemblage. For these calculations, the rim compositions of the amphiboles were used and yielded pressures in the range of 0.27 to 0.31 GPa which corresponds to an intrusion depth of less than 10 km. Temperatures were obtained with the hornblende-plagioclase thermometer using the calibration of Holland and Blundy (1994) and yielded temperatures in the range of 640-700°C. These data are in good agreement with similar pressure and temperature estimates of 0.24 to 0.36 GPa and 640 to 710°C for the Ifinger- and Kreuzberg intrusions by Acquafredda et al. (1997) and are in agreement with the stability of andalusite according to the revised triple point by Pattison (1992) and Pattison et al. (2002).

7.2 Hornfels thermobarometry

Two-feldspar thermometry: Newly formed K-feldspar and plagioclase were only observed in the rock fragments from the Kreuzberg deep drilling (Figures 3A, B). Equilibration temperatures were calculated with the computer software SOLVCALC 2.0 (Wen and Nekvasil, 1994) using the feldspar mixing model of Fuhrman and Lindsley (1988) with stated uncertainties of ±30°C. Two feldspar temperatures were calculated at a pressure of 0.3 GPa and a compositional uncertainly of ±0.02 mol. % and yielded temperatures in the range of 577°C to 641°C

Sample	Pl CKB 1	PlCKB 2	Pl CKB 3	Pl CKB 4	Pl CIF 1	Pl CIF 2	Pl CIF 3
SiO_2	58,95	57,82	60,27	59,28	61,46	61,99	61,58
TiO_2	n.d.	0,02	0,01	0,01	0,01	0,02	n.d.
$A_{l2}O_3$	24,99	25,35	24,38	24,94	23,50	23,60	23,60
Fe_2O_3	0,36	0,38	0,16	0,37	0,25	0,01	0,15
FeO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
MnO	n.d.	n.d.	n.d.	0,04	n.d.	0,03	n.d.
MgO	0,03	n.d.	0,02	0,01	n.d.	n.d.	n.d.
CaO	6,50	7,12	6,95	7,52	6,31	6,30	6,13
Na_2O	7,60	7,45	8,19	7,82	8,61	8,61	8,59
K_2O	0,61	0,41	0,27	0,43	0,20	0,14	0,08
Total	99,04	98,55	100,24	100,42	100,34	100,70	100,13
Si	2,651	2,614	2,671	2,628	2,718	2,731	2,729
Ti	n.d.	0,001	<0.001	<0.001	<0.001	0,001	n.d.
Al	1,324	1,351	1,273	1,303	1,225	1,226	1,232
Fe^{3+}	0,012	0,013	0,005	0,013	0,008	n.c.	0,005
Fe^{2+}	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Mn	n.d.	n.d.	n.d.	0,002	n.d.	0,001	n.d.
Mg	0,002	n.d.	0,001	0,001	n.d.	n.d.	n.d.
Ca	0,313	0,345	0,330	0,357	0,299	0,298	0,291
Na	0,662	0,653	0,704	0,672	0,738	0,735	0,738
K	0,035	0,024	0,015	0,024	0,011	0,008	0,005
An	0,310	0,338	0,315	0,339	0,285	0,286	0,282
Ab	0,656	0,639	0,671	0,638	0,704	0,706	0,714
Or	0,034	0,023	0,014	0,023	0,011	0,008	0,004

Table 2: Representative electron microprobe analyses of plagioclase. CKB: plagioclase analyses from the Kreuzberg contact aureole; CIF: plagioclase analyses from the Ifinger contact aureole. Formulae were calculated on the basis of 8 oxygens and 5 cations using the program NORM Version 4.0 (Ulmer, 1993, written com.). n.d.: not detected; Fe^{3+} calculated according to charge balance considerations. An: anorthite, Ab: albite, Or: K-feldspar.

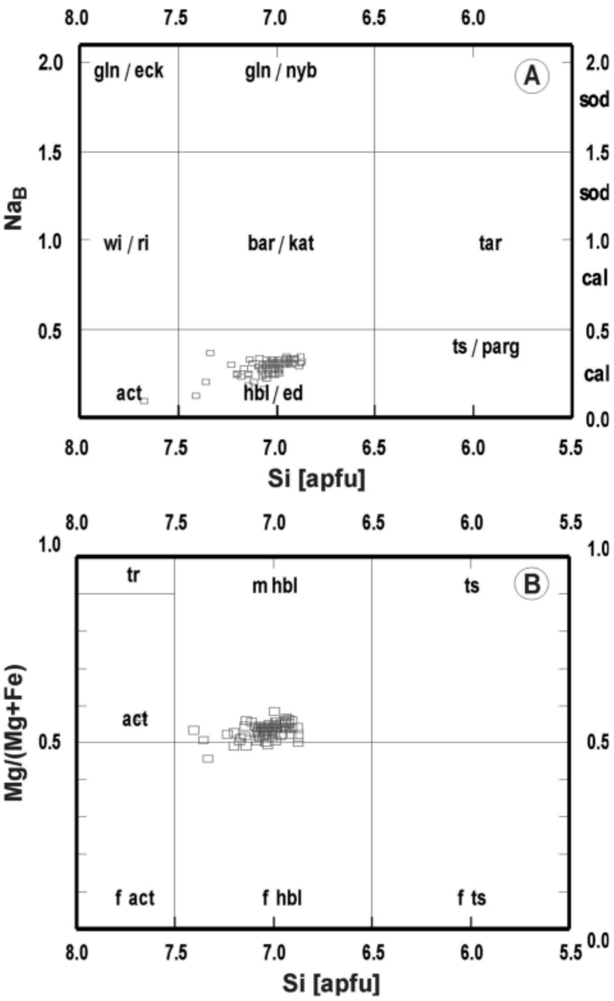

Figure 6: (A) Na^B vs. Si amphibole classification; (B) Mg/(Mg+Fe) vs. Si amphibole classification. The amphiboles can be classified as Mg-hornblendes according to Leake et al. (1997, 2004). Sample IF.

(Figure 7).

Ti-in-biotite thermometry: due to the lack of fresh cordierite, temperatures from contact metamorphic samples of the Ifinger contact aureole could not be calculated using phase equilibrium calculations but only by using minor element thermometry such as the Ti-in-biotite thermometer of Henry and Guidotti (2002) and Henry et al. (2005). Although Henry et al. (2005) formulated the Ti-in-biotite thermometer for graphitic metapelites that contain graphite, quartz, rutile and/or ilmenite in excess and equilibrated at pressures of roughly 0.4-0.6 GPa, the thermometer can be used for non-graphitic metapelites and still produces reasonable temperatures, however the calculated temperatures tend to be more erratic (Henry et al., 2005). In this study the Ti-in-biotite thermometer was applied to non-graphitic contact metamorphic metapelites which contained Ti-minerals such as rutile and ilmenite. For the calculations newly formed contact metamorphic biotites from both contact aureoles were used. Calculated temperatures of the Ifinger contact aureole yielded an average temperature of 667±15°C (Figure 8). Calculated temperatures of biotites from rock fragments of the Kreuzberg deep drilling yielded a similar average temperature of 677±19°C (Figure 8). The reason for this discrepancy of ca. 50°C when compared to two-feldspar thermometry and the petrogenetic grid of Pattison et al. (2002) most likely lies in the fact that the thermometer is used slightly outside of the calibrated pressure range and the lack of graphite in the samples. Therefore these biotites are enriched in Ti relatively to the calibrated Ti-saturation surface and hence the calculated temperatures have to be considered to be too high (Henry et al., 2005).

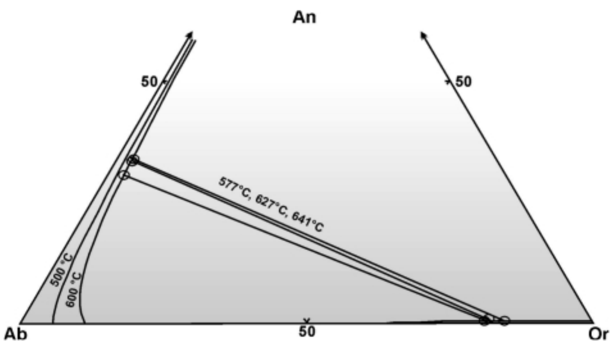

Figure 7: Two feldspar temperatures of the Kreuzberg contact aureole calculated with the computer program SOLVCALC 2.0 (Wen and Nekvasil, 1994) using the feldspar mixing model of Fuhrman and Lindsley (1988). Sample CKB.

Thermobarometry using the petrogenetic grids of Pattison et al. (2002): Due to the lack of sufficient phases for precise P-T calculations in the hornfelses, the approach using the petrogenetic grids of Pattison et al. (2002), contoured for X_{Mg} in biotite as a function of pressure, was used. Pattison et al. (2002) thermodynamically modelled petrogenetic grids in the system KFMASH, using two different aluminum silicate triple points, namely the Holdaway (1971) and Pattison (1992) triple points, which satisfy most of the natural and experimental constraints for the low-P assemblage muscovite + cordierite + andalusite + biotite + quartz ± sillimanite. These petrogenetic grids were then contoured in terms of X_{Mg} of biotite. Our samples from the hornfelses show X_{Mg} values ranging from 0.29 to 0.38 which corresponds to pressures between 0.25 and 0.35 GPa when using the aluminum silicate triple point of Pattison (1992). These pressures can then be reconciled with the occurrence of andalusite at temperatures up to 640°C, which was verfied by two-feldspar thermometry in the Kreuzberg contact aureole. Due to the lack of K-feldspar in samples from the Ifinger contact aureole, these temperatures can then also be considered as maximum temperatures. Using the Holdaway (1971) triple point yields slightly lower pressures ranging from 0.15 to 0.25 GPa, but andalusite stability cannot be reconciled with the obtained temperatures anymore.

8. Discussion

During the Permian the Southalpine domain has been affected by widespread magmatic activity that produced large basic to acidic volcanic and plutonic bodies (Del Moro and Visonà, 1982) In the central-eastern Southern Alps the Permian magmatic event is represented by the Cima d´Asta, Brixen-Klausen, Ifinger, Kreuzberg, Monte Sabion intrusions and by the volcanic areas of the Athesian Volcanic Group ("Bozner Quarzporphyr") and the Monte Locu volcanics (Bargossi et al., 1979; Bonin et al., 1993) These intrusive and extrusive bodies are interpreted as large calc-alkaline magmatic associations of Permian age which were originating through complex interactions between mantle-derived magmas and crustal materials (Rottura et al., 1997, 1998; Marocchi et al., 2008).

The emplacement of the Ifinger granodiorite (ca. 290-280 Ma) into the Southalpine basement in a shallow crustal level produced a contact aureole at the south western rim of the intrusion. Although thermobarometry of the intrusion yielded P-T conditions of 0.25-0.31 GPa and 630-670°C and these data indicate near-solidus conditions for the granodiorites, they are difficult to interpret due to amphibole growth over a large P-T range. Therefore it is somewhat uncertain to consider these P-T estimates to be close to the emplacement conditions. On the other hand, these results are consistent with the geological and petrographic evidence indicative of shallow-level granitoid magmatism in the Southalpine domain (Acquafredda et al., 1997). More robust constraints in terms of pressure and temperature of the contact metamorphic overprint were obtained by using the presence of andalusite, and reconcile it with the aluminum silicate triple point by Pattison (1992) and the petrogenetic grids of Pattison et al. (2002). This approach yielded pressures ranging from 0.25 to 0.35 GPa at temperatures <640°C. Due to the presence of considerable albite component in K-feldspar, pressures obtained with this approach will still mostly represent lower pressure estimates since an extension into the system KNFMASH will likely raise the phase relations in terms of pressure (e.g. Cesare, 1994). These data then indicate that emplacement and contact metamorphism also took place in a similar depth level as calculated with the Al-in-hornblende barometry.

Since contact metamorphic samples from the Kreuzberg contact aureole were only observed in the cuttings from the drilling project and the Ifinger contact aureole is strongly retrogressed, textural relations are obscure and chemical data of contact metamorphic minerals are sparse. On the other hand, due to the similarity of the basement rocks (Brixen quartzphyllite), which comprised the protoliths of the hornfelses in both contact aureoles, a direct comparison with the well-established mineralogical and chemical changes as well as thermobarometric data from the contact aureole in the south of the Brixen granodiorite (Wyhlidal et al., 2007a, b, 2008), allows several inferences about the prograde and retrograde history of these contact aureoles:

8.1 Textural comparison with the Brixen contact aureole:

Prograde evolution: The Southalpine basement contains in the northern part the mineral assemblage chlorite + muscovite + biotite + albite + quartz ± garnet (Sassi and Spiess, 1993; Ring and Richter, 1994). Although our samples represent the highest-grade stages of contact metamorphism and no definitive intermediate stages could be observed, it is still possible to propose model mineral reactions, based on the observed mineral reactions from the Brixen contact aureole. Contact metamorphic biotite and cordierite (only present as pinite) formed due to the reaction:

Muscovite + Chlorite + Quartz = Biotite + Cordierite + H_2O (1)

This reaction leads to a string decrease in the modal content of chlorite. The formation of anorthite-rich plagioclase can be

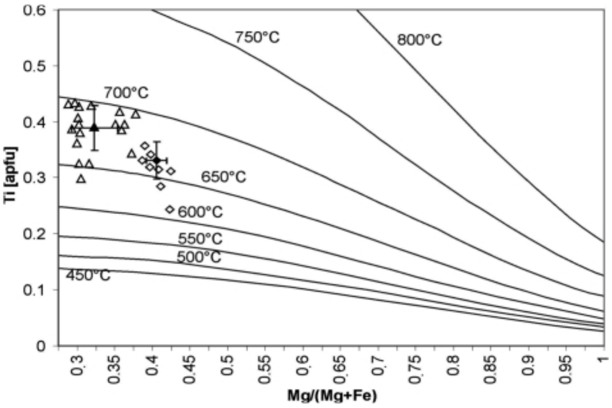

Figure 8: Ti-in-biotite thermometry of the Ifinger- and Kreuzberg contact aureole. Results of the Ti-in-biotite thermometry of the Ifinger contact aureole are shown as diamonds and those of the Kreuzberg contact aureole are shown as triangles. Temperatures were calculated according to the Ti-in-biotite geothermometry of Henry and Guidotti (2002) and Henry et al. (2005).

Sample	Kfs 1	Kfs 2	Kfs 3	Kfs 4	Kfs 5	Kfs 6
SiO_2	64,27	64,38	64,25	64,05	64,54	64,57
TiO_2	0,03	0,01	n.d.	0,03	0,02	0,01
Al_2O_3	18,27	18,19	18,40	18,20	18,04	18,00
Fe_2O_3	0,19	0,18	0,11	0,47	0,23	0,18
CaO	0,14	0,04	0,09	0,05	0,09	0,07
Na_2O	2,23	1,56	1,68	1,05	1,13	0,84
K_2O	13,64	15,00	14,67	15,64	15,60	16,17
Total	98,77	99,37	99,23	99,49	99,65	99,83
Si	2,980	2,976	2,972	2,967	2,983	2,982
Ti	<0.001	<0.001	n.d.	0,001	0,001	<0.001
Al	0,998	0,991	1,003	0,994	0,983	0,980
Fe^{3+}	0,007	0,006	0,004	0,016	0,008	0,006
Ca	0,007	0,002	0,004	0,003	0,004	0,003
Na	0,201	0,140	0,151	0,095	0,102	0,075
K	0,807	0,884	0,865	0,924	0,920	0,953
An	0,007	0,002	0,004	0,003	0,004	0,003
Ab	0,198	0,136	0,148	0,093	0,099	0,073
Or	0,795	0,862	0,848	0,905	0,897	0,924

Table 3: Representative electron microprobe analyses of K-feldspar. K-feldspar analyses from the Kreuzberg contact aureole. Analyses 1-3 represent the second generation and analyses 4-6 represent the first generation K-feldspars. Formulae were calculated on the basis of 8 oxygens and 5 cations using the program NORM Version 4.0 (Ulmer, 1993, written com.). n.d.: not detected; Fe^{3+} calculated according to charge balance considerations. An: anorthite, Ab: albite, Or: K-feldspar.

explained by a reaction involving Variscan garnet such as:

Chlorite + Garnet + Muscovite + Quartz = Biotite + Plagioclase + H_2O (2)

and andalusite formed due to the reactions (e.g. Pattison et al., 2002):

Muscovite + Cordierite = Andalusite + Biotite + Quartz + H_2O (3)
Muscovite + Quartz = K-Feldspar + Andalusite + H_2O (4)

Reactions (3) and (4) are very relevant for samples from the innermost contact aureole, since almost no muscovite occurs anymore.

Retrograde evolution: In addition to the prograde features which were described above, there are many textures within the Ifinger contact metamorphic assemblages from the Gilf ravine, which indicate retrograde reactions taking place subsequently after the contact metamorphic overprint. Based on petrographic observations, four retrograde textures and reactions can be derived. The major features are 1.) the partly alteration of biotite at the rims to chlorite and 2.) the retrogression of cordierite to pinite (Figures 9 A, B). Cordierite is much more susceptible to alteration than biotite. Both retrograde textures suggest that the retrogressions can be described with the reaction:

Biotite + Cordierite + H_2O = Muscovite + Chlorite + Quartz (5)

3.) Andalusite is always rimmed by late-stage muscovite and/or a felt of sericite or by intergrowths of white mica and quartz (Figure 9A) which can be described via the model reaction:

Andalusite +K-feldspar + H_2O = Muscovite + Quartz (6)

These retrogression features are thought to be the results of two different mechanisms: triggering of retrograde reactions through percolating H_2O-rich fluids liberated during cooling and crystallization of the pluton and/or due to the close vicinity of major fault lines adjacent to the plutons. 4.) In addition, albite-rich rims can form due to a late-stage Na-rich fluid interacting with anorthite-rich plagioclase according the reaction:

$CaAl_2Si_2O_8 + 2\ Na^+ + 4\ SiO_2{,}aq = 2\ NaAlSi_3O_8 + Ca^{2+}$ (7)

8.2 Mineral chemical comparison with the Brixen contact aureole:

The chemical compositions of contact metamorphic minerals such as biotite and plagioclase from the Ifinger- and the Kreuzberg contact aureoles can also directly be compared with the chemical data from the Brixen contact aureole. The average Ti content of biotites from zone IV (cordierite + andalusite + biotite, inner Brixen contact aureole) are 0.34±0.03 apfu and those from the Ifinger aureole are very similar with an average value of 0.35±0.03 apfu. The Ti content of biotite from the Kreuzberg aureole is slightly higher with an average value of 0.39±0.04 apfu, thus indicating most likely slightly higher temperatures. The X_{An} content of plagioclase from the Ifinger contact aureole is 0.284±0.002 and plagioclase from the Kreuzberg contact aureole also shows a similar anorthite content of 0.30±0.026. Both plagioclase compositions are also in good agreement with plagioclase composition (X_{An} = 0.315±0.06) from zone IV of the Brixen contact aureole.

8.3 Thermobarometric comparison with the Brixen contact aureole

Wyhlidal et al. (2007a, b) and Wyhlidal (2008) performed geothermobarometric calculations at 0.3 GPa using pseudosections, minor element thermometry and two-feldspar thermometry. Ti-in-biotite temperatures yielded for the innermost contact aureole a maximum average temperature of 656±14°C. Using two-feld-

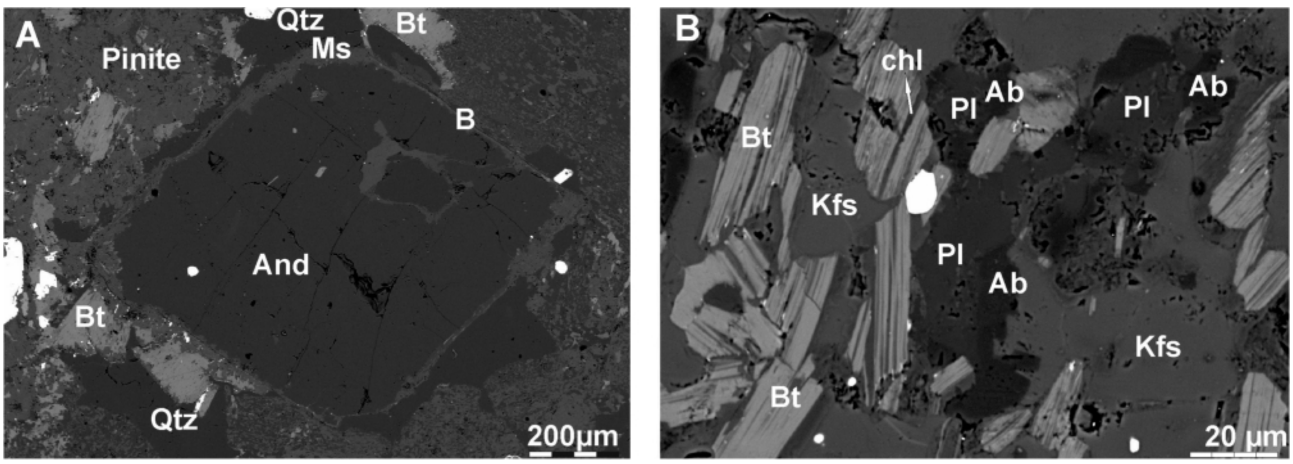

Figure 9: BSE images illustrating retrograde features in the samples from the Ifinger contact aureole (sample CIF). (A) Cordierite altered to pinite and andalusite altered to muscovite. (B) Plagioclase showing albite-rich rims and biotite altered to chlorite. Both features indicate retrogression during cooling.

spar thermometry, the innermost area yielded a maximum average temperature of 609±21°C. These temperatures are in good agreement with the temperature estimates from the hornfels samples from the two contact aureoles investigated in this study, thus indicating that the investigated samples most likely represent similar positions within the contact aureoles, namely parts of the innermost contact aureoles.

These petrological and mineral chemical observations allow drawing the following conclusions concerning the contact aureoles of the Ifinger and Kreuzberg plutons:

(1) Hornfelses from the Ifinger contact aureole and contact metamorphic rock fragments from the deep drilling cuttings near Meran can be directly compared with hornfelses of zone IV (cordierite + andalusite + biotite) formed at the southern rim of the Brixen granodiorite. Thus in terms of petrography only the innermost areas of the contact aureoles of the Ifinger Granodiorite and the Kreuzberg Granite were most likely encountered.

(2) The outhermost areas of the contact aureoles are totally altered due to the close vicinity of major fault lines.

(3) The estimated temperature conditions yielded a maximum temperature of <680°C for the innermost contact aureole based on Ti-in-biotite thermometry and 570-640°C when using two-feldspar thermometry, which is also in agreement with thermometric data from the innermost part of the Brixen contact metamorphic aureole.

(4) The depth of contact metamorphism was most likely less than 10 km in agreement with the occurrence of andalusite in the hornfelses as well as in the Ifinger granodiorite samples and also in agreement with the aluminium silicate triple point of Pattison (1992) and the results of the petrogenetic grids of Pattison et al. (2002) for the assemblage muscovite + cordierite + andalusite + biotite + quartz ± sillimanite.

Sample	Amph1	Amph2	Amph3	Amph4	Amph5	Sample	Pl1	Pl2	Pl3
SiO_2	47,13	46,16	46,66	46,16	46,71	SiO_2	58,71	58,91	58,23
TiO_2	0,96	0,95	1,10	1,11	0,93	TiO_2	0,01	0,01	0,02
Al_2O_3	6,78	7,03	6,99	6,88	6,96	Al_2O_3	25,63	25,58	25,49
Fe_2O_3	3,30	4,07	4,24	3,79	3,98	Fe_2O_3	0,17	0,10	n.c.
FeO	16,39	16,25	16,80	15,86	16,58	FeO	n.d.	n.d.	0,08
MnO	0,69	0,74	0,77	0,60	0,64	MnO	0,01	0,03	n.d.
MgO	9,62	9,46	9,12	9,51	9,77	MgO	n.d.	0,03	n.d.
CaO	10,53	10,34	10,55	10,69	10,16	CaO	7,71	7,81	7,59
Na_2O	1,19	1,26	1,37	1,22	1,22	Na_2O	7,09	7,06	6,85
K_2O	0,66	0,73	0,71	0,70	0,67	K_2O	0,37	0,39	0,41
Total	97,25	96,99	98,31	96,52	97,62	Total	99,70	99,90	98,67
Si	7,089	6,991	6,991	7,009	7,018	Si	2,632	2,636	2,640
Ti	0,109	0,108	0,124	0,126	0,105	Ti	<0.001	<0.001	0,001
Al	1,202	1,255	1,235	1,232	1,233	Al	1,354	1,349	1,362
Fe^{3+}	0,374	0,464	0,478	0,433	0,450	Fe^{3+}	0,006	0,003	n.c.
Fe^{2+}	2,062	2,059	2,105	2,014	2,083	Fe^{2+}	n.d.	n.d.	0,003
Mn	0,087	0,095	0,098	0,078	0,081	Mn	0,001	0,001	n.d.
Mg	2,157	2,135	2,037	2,152	2,188	Mg	n.d.	0,002	n.d.
Ca	1,697	1,678	1,694	1,739	1,636	Ca	0,370	0,375	0,369
Na	0,347	0,369	0,398	0,360	0,357	Na	0,616	0,612	0,602
K	0,127	0,142	0,136	0,137	0,129	K	0,021	0,022	0,024
Total	15,251	15,296	15,296	15,280	15,280	Total	5,000	5,000	5,000
						Xan	0,368	0,371	0,371
P = GPa	0,27	0,30	0,29	0,29	0,29	Xab	0,611	0,607	0,605
T = °C	653	689	698	685	685	Xor	0,021	0,022	0,024

Table 4: Representative electron microprobe analyses of plagioclase and amphibole Coexisting amphibole and plagioclase analyses from the Ifinger granodiorite (sample IF). Plagioclase formulae were calculated on the basis of 8 oxygens and 5 cations using the program NORM Version 4.0 (Ulmer, 1993, written com.). Amphibole formulae were calculated with the program PET (Dachs, 2004). n.d.: not detected; Fe^{3+} calculated according to charge balance considerations. An: anorthite, Ab: albite, Or: K-feldspar.

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Stefan WYHLIDAL[1)], Werner Friedrich THÖNY[1)], Peter TROPPER[1)*)] & Volker MAIR[2)]

[1)] Institute of Mineralogy and Petrography, Faculty of Geo- and Atmospheric Sciences, University of Innsbruck, Innrain 52, A-6020 Innsbruck, Austria;

[2)] Amt für Geologie und Baustoffprüfung, Eggentalerstrasse 48, I-39053 Kardaun (BZ), Italy;

[*)] Corresponding author, peter.tropper@uibk.ac.at